Subsurface geometry and segmentation of the Palos Verdes Fault and their implications for earthquake hazards in southern California

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Investigations Undertaken

This project investigates the structural geometry, kinematics, and earthquake potential of the Palos Verdes Fault (PVF) in southern California, and represents the doctoral dissertation research of Charles Brankman. Using an extensive data set of industry seismic reflection profiles and petroleum well data, the three-dimensional subsurface geometry of the fault, including its dip and along-strike geometric segmentation, is being investigated. Geologic cross sections and balanced three-dimensional structural models will be used to define the deformational history and kinematics of the fault, providing a basis to map slip and slip rate estimates to depth. This study also defines individual fault segments within the larger fault system, which limit the fault surface areas that might be expected to rupture during future earthquakes on the PVF. Implications of this study for earthquake hazards will be addressed by re-assessing possible magnitudes of earthquakes that rupture all or parts of the fault system, based on our improved definition of the fault size, shape, and along-strike geometric segmentation.

The PVF is recognized as a major structure in the western Los Angeles basin (Figure 1), extending over 100 km from the eastern margin of the uplifted Palos Verdes Hills southeast through the Port of Los Angeles and offshore across the San Pedro shelf. Numerous studies have focused on defining the location, activity, and slip rate of the fault (e.g. Woodring et al., 1946; Yerkes et al., 1965; Wright, 1991; Dibblee, 1999; Marlow et al., 2000; Bohannon et al., 2004). However, there is currently no consensus about the fault's subsurface geometry, along-strike geometric segmentation, northern and southern terminations, or detailed sense of slip. In addition, the relationship of the PVF to many of the adjacent, and potentially active, fault systems (e.g., THUMS and Compton faults), is not well understood.

A primary question about the PVF, and of significant relevance to earthquake hazard models in the LA Basin, is whether the fault is a near-vertical, right-lateral strike-slip fault, or if it dips more gently and accommodates a significant component of dip slip. Along the onshore portion of the fault, Wright (1991) documented a 1200 m vertical offset of the top of basement across a west-dipping fault surface that bounds the northeast side of the Palos Verdes Peninsula. Consistent with this interpretation, Ward and Valensise (1994), in a study of uplifted marine terrace remnants on the Palos Verdes Peninsula, used numerical fault models to interpret the PVF as a right-oblique reverse fault and obtained good matches to the terrace elevation data. These authors proposed that the reverse component of slip and west dipping fault segment form a restraining bend, but that the dipping fault segment is generally limited to the onshore portion of the fault.

To the south along strike, the fault has generally been considered to be vertical with purely right-lateral strike slip displacement. This is consistent with a number of steeply dipping to near-vertical faults splays that have been mapped in the offshore Beta oil field along the PVF (Kelsch et al., 1998; Rigor, 2003). In addition, shallow paleoseismic studies onshore and in the Los Angeles Harbor (Stephenson et al., 1995; McNeilan et al., 1996) interpreted near-vertical faults, with nearly pure strike-slip displacement of about 2.5-3.8 mm/year. This vertical fault model currently forms the basis for earthquake hazard estimates of the fault. However, other authors (Davis et al., 1989; Shaw and Suppe, 1996) have interpreted that at depth the PVF has a southwestern dip and a significant reverse component of displacement along its entire extent, which may significantly affect these hazard estimates.

Results

In order to address these first-order questions about the structural geometry of the PVF, we have performed a systematic mapping of the stratigraphic units and structural features in the Inner Borderlands region south of the Palos Verdes Peninsula, using seismic reflection data collected during petroleum exploration. Eighteen seismic reflection lines, comprising approximately 800 km of data and covering the region along the PVF south of the Palos Verdes Peninsula, were digitized and vectorized. An additional several thousand kilometers of digital seismic data was obtained from the USGS through the National Archive of Marine Seismic Surveys (http://walrus.wr.usgs.gov/NAMSS). These data were imported into a PC-based seismic data project to facilitate mapping and structural interpretation (Figure 1). In addition, stratigraphic and velocity data from several petroleum industry exploration wells in the area were included in the project to facilitate interpretation of stratigraphic surfaces. Stratigraphic picks from the wells included the top of crystalline basement (Catalina schist), and a series of regionally extensive sedimentary units including Mohnian; Delmontian; lower and upper Repetto; lower, middle, and upper Pico; and top Pleistocene.

Figure 2 shows a representative seismic line across the San Pedro Shelf, south of the Palos Verdes Peninsula, which illustrates several of the structural features that characterize this trend. At this location, the PVF in the upper 3-4 km is expressed as a near-vertical zone of incoherent and disrupted reflectors west of an undeformed basin filled with Miocene and later sediments. West of the fault, the Miocene units are deformed in contractional folds, thinning onto a prominent basement high. Within these contractional folds, the wedge of Neogene strata thickens toward the fault, and exhibits an internal fanning of limb dips that records down-to-the-fault rotation of the underlying basement block. Maximum thicknesses of units west of the fault are greater than the thicknesses of the corresponding units east of the fault. In addition, the stratigraphic horizons are structurally higher west of the fault than their corresponding horizons east of the fault. Finally, repetition and overthrusting of the basement reflector is observed at the base of the near-vertical shallow fault zone. These features are consistently observed along the PVF in the northern portion of the study area. Figure 3 shows a depth-converted seismic line with interpretation of structural and stratigraphic features.

The geometry of sedimentary units described above is consistent with, and indicative of, deposition of growth strata in the hanging wall above a west-dipping fault with normal displacement (Hamblin, 1965; Xiao and Suppe, 1992). This interpretation is consistent with the known period of Miocene normal faulting that accommodated pure or oblique crustal extension (Crouch and Suppe, 1993; Rivero et al., 2000). Furthermore, the presence of structurally higher horizons west of the fault indicates that these units must have been structurally inverted, or uplifted, in a contractional phase of deformation subsequent to the extension. This contractional deformation is consistent with the overthrusting (structural duplication) of the basement surface by east-directed reverse faulting as imaged in the seismic data. Thus, we interpret these structural and stratigraphic patterns to reflect that the Palos Verdes fault has reactivated a large, Miocene age normal fault. Based on the stratigraphic correlations, this inversion occurred in the late Pliocene to Pleistocene, at the inception of the modern oblique, right-lateral reverse fault system, and appears to have generated the younger contractional folding and generated (or enhanced) the vertical fault splays.

These structural observations and their implied fault kinematics are most compatible with a southwest dip component of the Palos Verdes fault at depth in this region. This southwesterly dip is confirmed by the seismic images that show the top of basement and Tertiary strata duplicated (overthrust) by the Palos Verdes fault (Figure 2B), in a position below the imaged vertical fault splays. In depth profiles, hanging wall and footwall cut-offs constrain the fault to dip less than 55° to the southwest. Thus, the southwestern dipping portion of the Palos Verdes fault appears to extend well south of the onshore Peninsula.

Farther to the south, the fault structure in the shallow subsurface changes character. Figure 4 shows a profile approximately 20 km south of the Peninsula, and shows structures and stratigraphic relationships similar to those observed in Figure 2. Eastward thickening Miocene growth strata is deformed by contractional folding, and the shallow, near-vertical fault zone is similar to that in Figures 2 and 3. However, this fault zone is located in the hanging wall of a well-imaged east-dipping reverse fault and associated anticline that accommodates a component of NE-SW contraction. The geometry of the east-dipping reverse fault, and the deformation of the Miocene growth sediments, is consistent with this fault representing either (1) a backthrust originating from the underlying west-dipping normal fault surface, which has been structurally inverted in compression; or (2) a younger reverse fault which crosscuts and offsets the earlier normal fault. In addition, a second, minor west-dipping reverse fault is present west of the PVF, and this structure dies to the north and south into an anticline-syncline pair (see Figure 6).

To the south near Lasuen Knoll, the fault system exhibits different structural details that are nevertheless consistent with reverse displacements and non-vertical fault geometries (Figure 5). The PVF is emergent at the base of the western margin of Lasuen Knoll (off the seismic section). Dip-slip components of motion result in contractional growth folding that is expressed on the east side of the Knoll. The geometry of the folded sediments on the eastern flank of the uplifted block is consistent with reverse displacement on the east-dipping reverse fault that can be traced southeast along strike from the location of Figure 3. Similar to Figure 3, this fault may be a backthrust above the inverted west-dipping normal fault, or continue to deeper levels as an east-dipping reverse fault that crosscuts the older normal fault. We prefer the backthrust/wedge interpretation as it is most consistent along the length of the PVF. These contractional growth structures are similar to structures documented above blind thrust faults elsewhere in southern California (Shaw and Suppe, 1994; 1996), and thus can be used to constrain the magnitudes and long-term rates of the contractional component of fault motion.

A structure map of the region (Figure 6) and a map of the basement surface (Figure 7) show the regional character of deformation, highlighting the locations and displacements of the major segments of the PVF. At least three well-defined fault segments (informally named here F1, F2, and F3) intersect and offset the basement surface. A near-vertical, southeast-trending fault zone (F1) extends from the northern edge of the study area southwest, corresponding approximately to the mapped trace of the PVF (Jennings, 1994; Fisher et al., 2004). This fault zone is well imaged for approximately 13 km. Although the 1 km-wide fault zone corresponds to a zone of reduced seismic reflectivity and highly disrupted reflectors, the basement surface is clearly offset by up to 800m across the fault, with the west side displaced up (Figure 2). Below a depth of approximately 3km, the top of basement and Tertiary strata are duplicated (overthrust) by the Palos Verdes fault, in a position below the imaged vertical fault splays. Hanging wall and footwall cut-offs constrain the fault dip to less than 55° to the southwest. Displacement across the fault appears to decrease to the south along the fault. A second major fault segment (F2) overlaps the southern portion of F1 and continues southeast across the study region. This fault is expressed clearly along its northern extent by a southwest-vergent folding and overthrusting of basement above an east-dipping fault, locally expressed in fault-plane reflections. F2 extends southeast and bounds an uplifted block of basement that forms Lasuen Knoll. A smaller fault segment (F3) is present subparallel to the northern portion of F2 and consists of a southwest-dipping, northeast-vergent fault plane that offsets basement in a reverse sense. This fault segment appears to extend only about 10km to the south, where it terminates into an anticline-syncline pair.

All three fault segments identified above show direct indications of fault geometry in the seismic data, and two (F2 and F3) are further constrained by direct fault plane reflections. The geometry of fault F1 appears to change from near-vertical in the upper 3km to moderately west-dipping below 3km. Mapping of other stratigraphic horizons has revealed patterns of sedimentary architecture that provide indications of the fault geometry at depth, as well as its structural evolution (Figures 2 and 4). The thicknesses of the Miocene sedimentary units vary greatly across F1. East of the fault, these units are nearly flat-lying, and have uniform thicknesses to the northeast. West of the fault, however, the thickness of the units varies dramatically. Units are thin or not present on the basement high west of F1, pinching out or onlapping on to the east-dipping basement surface. In turn, the units thicken markedly to the east toward the fault.

The structural and stratigraphic observations and their implied fault kinematics are most compatible with a southwest dip component of the Palos Verdes fault at depth in this region. Thus, the southwest-dipping portion of the Palos Verdes fault appears to extend well south of the onshore Peninsula. These observations provide immediate confirmation that neither the simple vertical fault model, nor the model of the reverse fault extending only beneath the uplifted onshore Palos Verdes Hills, is accurate or sufficient for the purposes of seismic hazards estimates.

While right-lateral strike-slip motion has been documented by paleoseismic studies (Stephenson et al., 1995; McNeilan et al., 1996) and using numerical fault models (Ward and Valencise, 1994), we propose that the strike-slip displacement cannot in itself explain the structural and stratigraphic relationships observed in the seismic data. A component of dip-slip displacement is evident along the entire length imaged in the seismic data. For instance, the structural inversion of Miocene strata across the fault, the contractional folding west of the PVF, and the prominent emergent structural block of Lasuen Knoll, all argue for significant dip-slip displacements. Uplift of Lasuen Knoll has previously been explained as a pop-up structure developed by strike-slip motion through a restraining bend fault architecture (Fisher et al., 2004). However, resolving right-lateral slip on the fault trace as mapped in the seismic data (see Figure 6) results in a releasing bend geometry. Thus, we conclude that purely strike-slip motion on the PVF is not sufficient to result in the large magnitude of uplift at Lasuen Knoll. It appears that strike-slip displacement is accommodated in the discrete shallow fault traces imaged in the seismic data, while the deeper fault slips in an oblique-reverse sense.

Ongoing regional mapping will refine the stratigraphic and structural relationships presented above. In addition, we will define permissible deep fault geometries, consistent with the observed shallow features, using kinematic models of growth deposition above normal faults and subsequent structural inversion. The result will be two-dimensional fault models that will then be linked into a 3D fault model that will serve as an accurate subsurface representation of the PVF.

Non-Technical Summary

The Palos Verdes Fault represents a significant earthquake source in southern California, however, the detailed geometry and structure of this fault are largely unknown. This study uses geophysical data collected by the petroleum industry to characterize the three-dimensional structure of the PVF. We find that the fault is composed of several interrelated fault segments, reflecting earlier periods of deformation and fault activity, and that the current fault segments are reactivated older faults. The PVF has a southwest dip, implying that current earthquake models of the fault relying on simple vertical fault models are inadequate to assess earthquake hazard from this fault.

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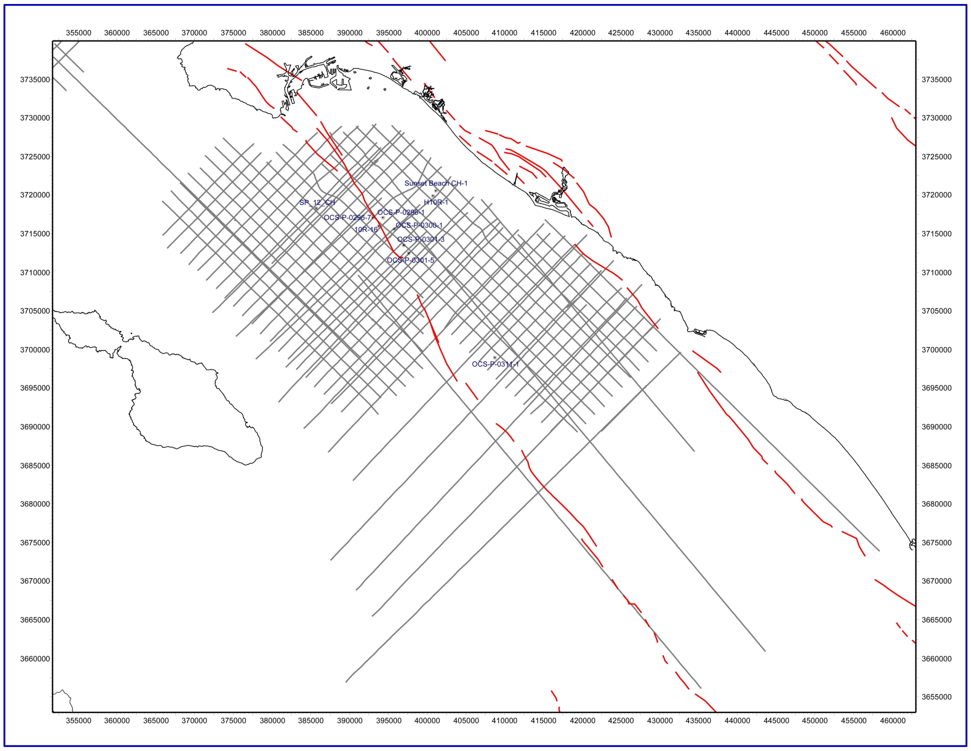

Figure 1. Location map of the San Pedro Bay region, showing the location of seismic lines used in this project. Red lines represent fault traces from Jennings (1994).

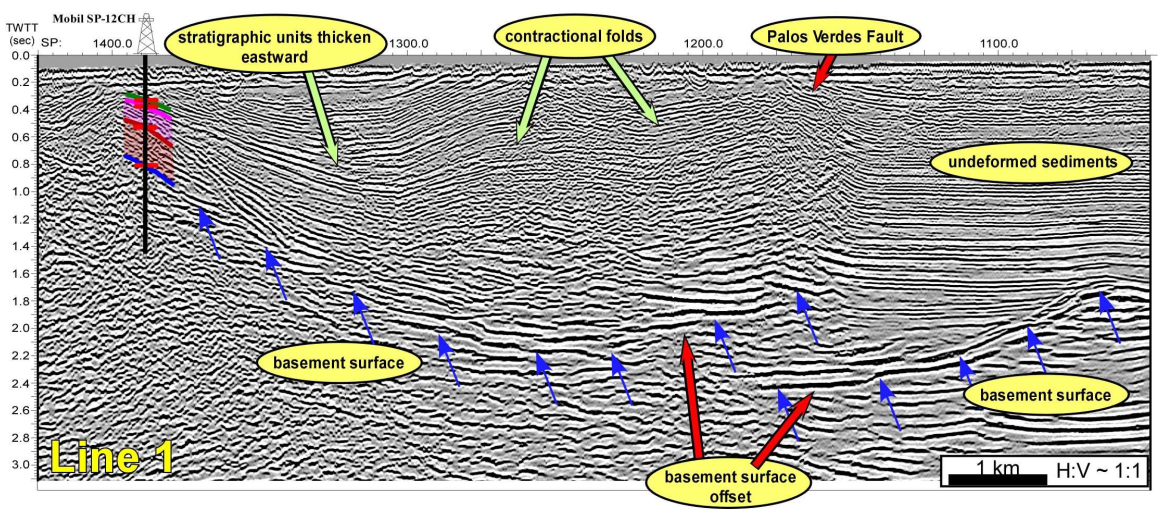

Figure 2. Seismic line (time section) showing structural and stratigraphic features which characterize the deformation surrounding the Palos Verdes Fault.

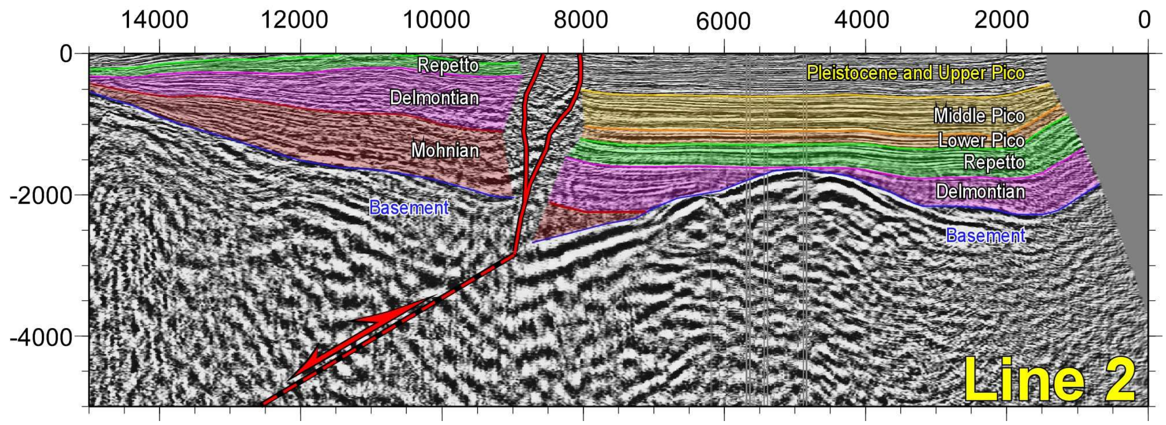

Figure 3. Seismic line (depth section) showing interpretations of stratigraphy and fault geometry in the region of San Pedro Shelf. See Figure 6 for location of line.

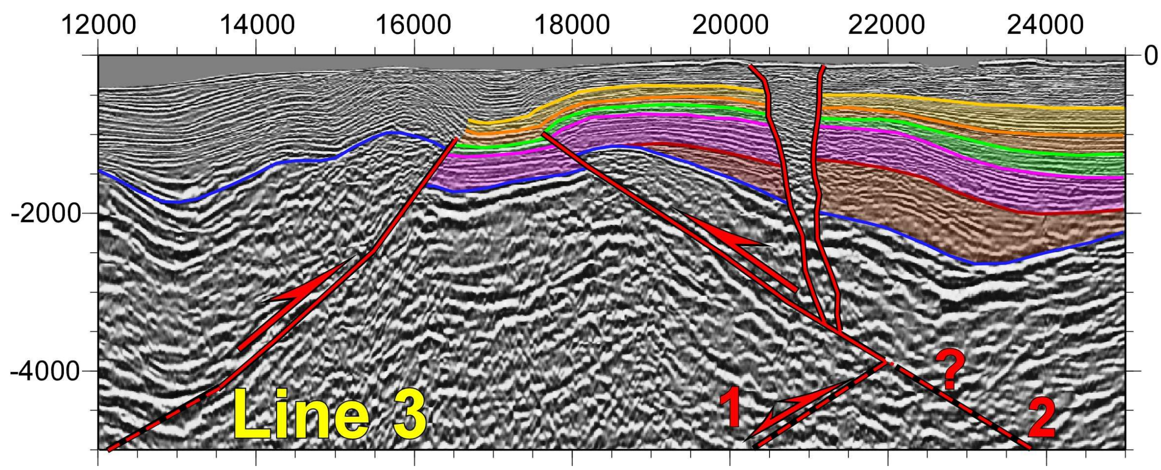

Figure 4. Seismic line (depth section) showing interpretations of stratigraphy and fault geometry and the transition to a more complex fault geometry than to the north. See Figure 6 for location of line.

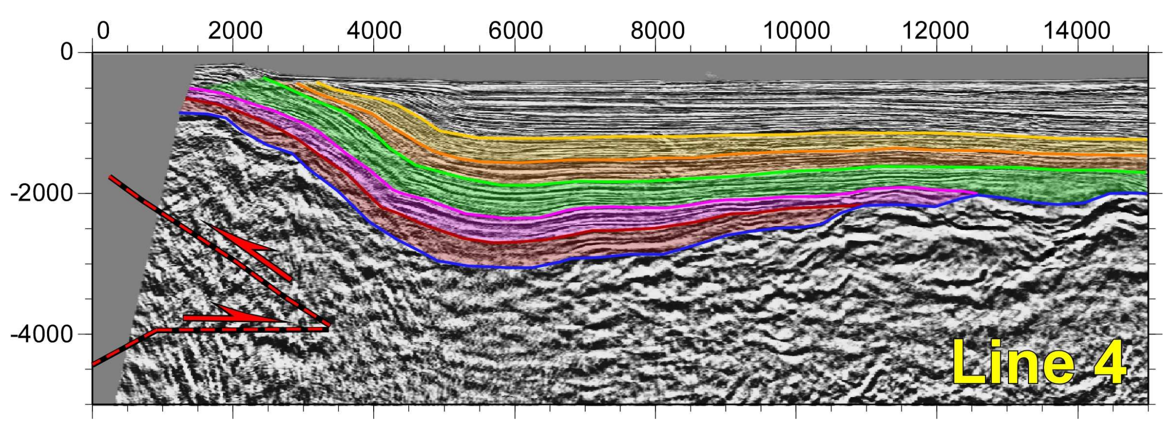

Figure 5. Seismic line (depth section) showing interpretations of stratigraphy and fault geometry in region of Lasuen Knoll. See Figure 6 for location of line.

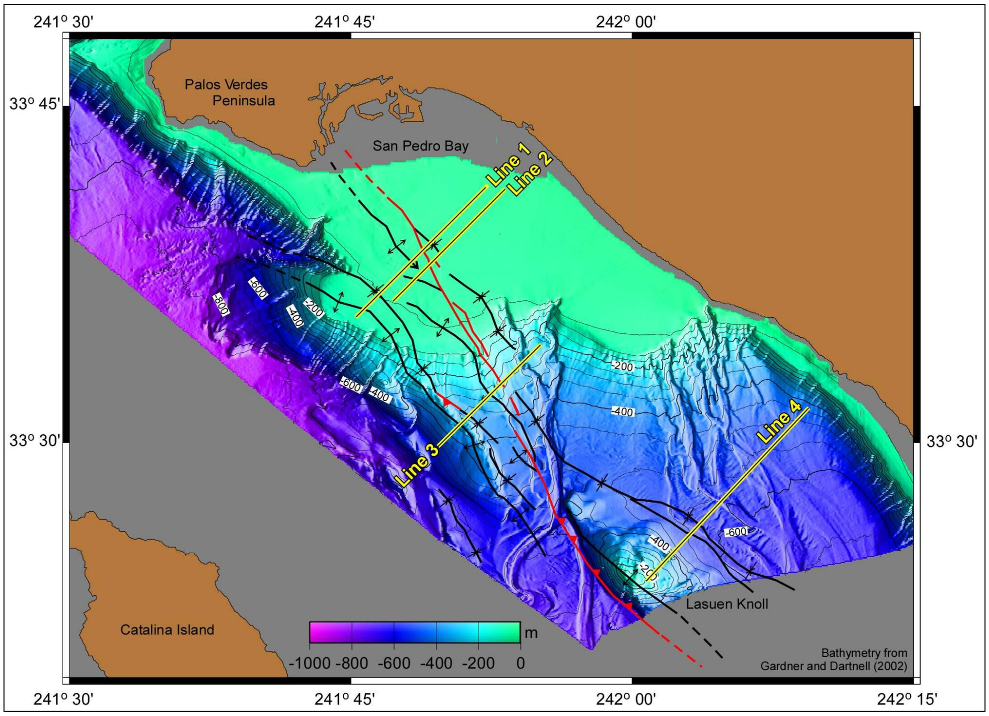

Figure 6. Map showing structures mapped from seismic reflection profiles overlaid on contours and shaded relief image of bathymetry (from Gardner and Dartnell, 2002). Locations of lines in figures 2-5 are shown.

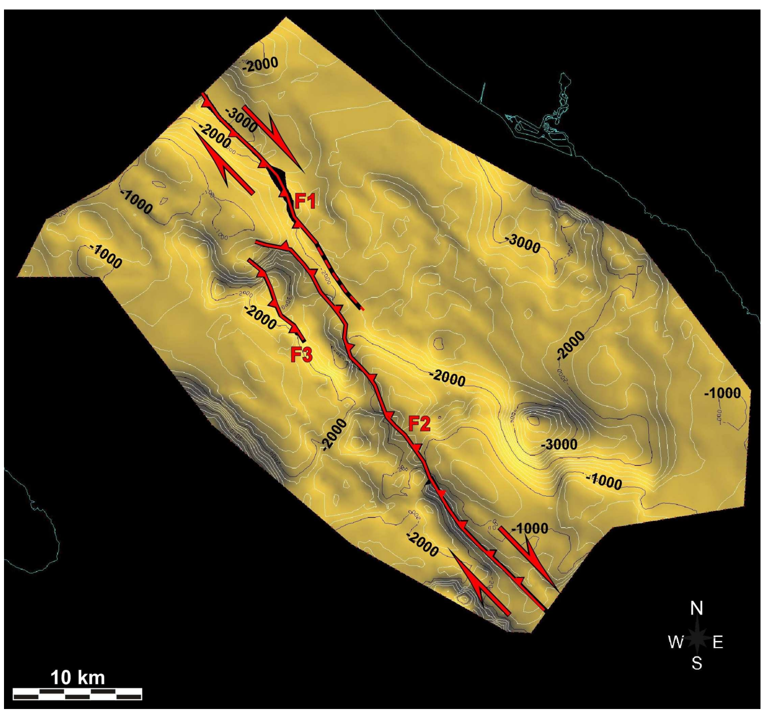

Figure 7. Contour map of top of basement, showing fault segments along the PVF. Segment F1 corresponds to the near-vertical trace of the PVF, with significant west-side-up and right-lateral strike-slip displacement. Segment F2 represents an east-dipping reverse (oblique-reverse?) fault that extends south to Lasuen Knoll. Segment F3 corresponds to a short west-dipping reverse fault that continues as an anticline north and south along strike.